BOTTOMONIUM AND CHARMONIUM RESULTS FROM CLEO

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Heavy Quarkonium Physics continues to be a focus of the work done by the CLEO Collaboration. We present several results in the spectroscopy of both bottomonium and charmonium systems using CLEO's data sets taken at the $\Upsilon(3S)$, $\Upsilon(2S)$ and $\psi(2S)$ resonances.

1 Introduction

In 2000, CLEO stopped running at the $\Upsilon(4S)$ for B-meson studies, and began an eight-year study of the states of bottomonium, charmonium and open charm mesons, the latter two of which were performed primarily as the experiment evolved into CLEO-c. We present here several results from our full charmonium and bottomonium data sets.

2 Hadronic Transitions

The study of hadronic transitions among heavy quarkonium states provides important tests for non-perturbative Quantum Chromodynamics (QCD) [1]. In the multipole expansion, [2] hadronic transitions among heavy quarkonium states proceed by emission and hadronization of soft gluons. The non-relativistic nature of the bottomonium system and the richness of the spectrum of bound states make it an excellent laboratory for the study of the low-q^2 hadronization process.

2.1 $\pi\pi$ Transitions

First, we report [3] improved measurements of the branching fractions for $\pi\pi$ transitions among the vector states of the bottomonium system. Dipion transitions from $\Upsilon(3S)$ to the lower vector states ($\Upsilon(2S)$, $\Upsilon(1S)$) and from $\Upsilon(2S)$ to $\Upsilon(1S)$ have been of interest ever since their first observation in 1982. There has recently been a resurgence of interest in dipion transitions following the observation of new $\pi^+\pi^-$ transitions by several experiments. Additional motivation

to update measurements of the branching fractions for bottomonium dipion transitions comes from the prospects of using $\Upsilon(3S), \Upsilon(2S)\to\pi\pi\Upsilon(1S)$ as a clean source of tagged $\Upsilon(1S)$ to study exclusive $\Upsilon(1S)$ decays, including searches for invisible decay modes.

In this analysis, we study the transitions both inclusively (in which case we detect only the pair of charged pions) and exclusively (in which case we detect, in addition to the charged or neutral pair of pions, the decay of the daughter $\Upsilon(nS)$ state to either $\mu^+\mu^-$ or e^+e^-). In each case, the primary quantity used to identify our observation of the dipion transitions of interest is mass recoiling against the dipion system. From the recoil mass histograms, yields for each process may be obtained and converted to the branching fractions presented in Table 1. In every case the branching fractions obtained are more precise than the current PDG [4] world average.

Table 1: Results of improved branching fraction measurements for the processes $\Upsilon(nS)\to\pi\pi\Upsilon(mS)$.

Mode	BF (%)	PDG BF (%)
$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$	$4.46 \pm 0.01 \pm 0.13$	4.48 ± 0.21
$\Upsilon(3S)\to\pi^0\pi^0\Upsilon(1S)$	$2.24 \pm 0.09 \pm 0.11$	2.06 ± 0.28
$\Upsilon(3S)\to\pi^0\pi^0\Upsilon(2S)$	$1.82 \pm 0.09 \pm 0.12$	2.00 ± 0.32
$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$	$18.02 \pm 0.02 \pm 0.61$	18.8 ± 0.6
$\Upsilon(2S)\to\pi^0\pi^0\Upsilon(1S)$	$8.43 \pm 0.16 \pm 0.42$	9.0 ± 0.8

2.2 η Transitions

We next present the first observation [5] of a transition in bottomonium involving η mesons. In order to produce a pseudoscalar meson η or π^0 in $\Upsilon(nS)\to(\eta,\pi^0)\Upsilon(mS)$ transitions (involving the flip of a heavy quark's spin), one quark of the hadronic system must emit an M1 (magnetic dipole) gluon while the other emits an M1 or E2 (electric quadrupole) gluon. The observation of the spin-flip of a b-quark can shed light on its chromomagnetic moment.

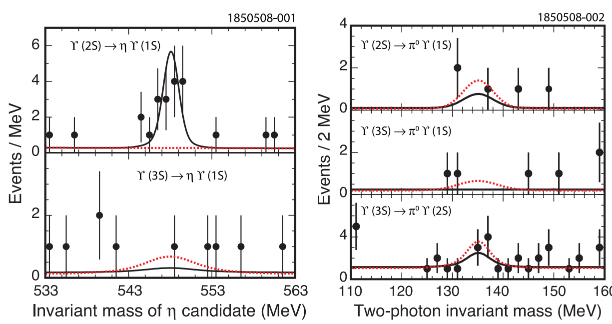

Figure 1: Invariant mass of (left) η and (right) π^0 candidates observed in transitions $\Upsilon(mS)\to\Upsilon(nS)+X(\gamma\gamma,\pi^+\pi^-\pi^0,3\pi^0)$.

In this analysis, the daughter Υ state is tagged via its decay to $\ell^+\ell^-$. Branching fractions are then obtained from the invariant mass distributions of the π^0 or η daughters. (See Figure 1) The backgrounds from various sources are very small, and expected to be linear in the region of interest. We thus obtain:

$$B(\Upsilon(2S)\to\eta\Upsilon(1S)) = (2.1^{+0.7}_{-0.6} \pm 0.3) \times 10^{-4}(5.3\sigma). \quad (1)$$

For the other π^0 or η transitions studied, only upper limits were obtained.

3 Hadronic Annihilation Decays

By contrast to the processes discussed above, hadronic annihilation of heavy quarkonia is a comparatively high q^2 process, and thus they probe quite different features of QCD.

3.1 $\chi_b(1P, 2P)$ Decays to Light Hadrons

CLEO has also, for the first time, observed [6] decays of bottomonia into light hadrons. Using data taken at the higher vector states $\Upsilon(3S)$ and $\Upsilon(2S)$, we tag the production of $\chi_b(1P, 2P)$ by observation of the appropriate E1 photons. We then reconstruct over 650 different exclusive final states, and obtain the yield from the invariant mass distributions for each. We observe fourteen

modes in which there are $> 5\sigma$ signals for each of $\chi_b(1P)$ and $\chi_b(2P)$, having branching fractions in the range $1 - 20 \times 10^{-4}$. These results can be of use in validating models of fragmentation of heavy states, and for exclusive reconstruction of η_b and h_b.

3.2 $\chi_b(1P, 2P)$ Inclusive Decays to Open Charm

We have also studied [7] inclusive decays of $\chi_b(1P, 2P)$ to open charm. For even-J states, we expect that hadronic decays occur via gg, whereas for the J=1 states, gg is forbidden, and the most probable intermediate state is $g + q\bar{q}$. We may test these expectations by seeking decays involving open charm, which would tend to be suppressed for gg and enhanced, with an expectation of $\approx 25\%$ of the hadronic rate for the $g + q\bar{q}$ intermediate state.

In this analysis, for events containing at least one D^0 the spectrum of detected photons is fitted to obtain rates of D^0 production from each χ_b state. The ratio $\mathcal{R}$ of the D^0 rate to the total hadronic rate (roughly the total width minus the radiative width in each case) is calculated. For the $J = 1$ states, we confirm theoretical expectations, obtaining: only were significant results obtained - and each confirms the expectation of $\approx 25\%$ for the $J = 1$ states:

$$\mathcal{R}(\chi_{b1}(1P)) = (24.8 \pm 3.8 \pm 2.2 \pm 3.6)\% \tag{2}$$

$$\mathcal{R}(\chi_{b1}(2P)) = (25.3 \pm 4.3 \pm 2.5 \pm 2.4)\%. \tag{3}$$

These results represent the first measurements for the $J = 1$ branching fractions and offer the opportunity for the refinement of models of $b\bar{b}$ hadronic annihilation decays.

4 Radiative Transitions and Decays

The study of radiative transitions and decays offers a third probe of QCD.

4.1 Annihilation of J/ψ to 3γ

An important test of QED has been the study of the 3γ decay of Ortho-positronium, and similarly the 3γ decay of ortho-charmonium, J/ψ, can serve as a laboratory for the investigation of the QCD by comparing the rate for this decay to the rates for γgg, ggg or $\ell^+\ell^-$. Prior to our observation [8] of this decay only Ortho-positronium was known to decay to $\gamma\gamma\gamma$.

Production of J/ψ was tagged via the process $\psi(2S) \to \pi^+\pi^- J/\psi$, and events containing three additional showers in the electromagnetic calorimeter were selected. Events for which the invariant mass of any pair of these showers corresponded to π^0, η, η' or η_c were removed. An excess of 24.2 events is observed on top of expected backrounds. We thus obtain

$$B(J/\psi \to \gamma\gamma\gamma) = (1.2 \pm 0.3 \pm 0.2) \times 10^{-5} (6\sigma), \tag{4}$$

with which zeroth order predictions [1] generally agree, but first-order perturbative QCD corrections are huge; this measurement presents a significant challenge, therefore, for theory.

4.2 Decays of Vector Charmonium to γ + Pseudoscalar Mesons

Naively, one expects that the ratio of decay rates of heavy quarkonia via γgg to that via ggg to scale as α/α_S. However, this is not borne out in the charmonium system; a recent CLEO-c measurement revealed the ratio for $\psi(2S)$ is only half of that for J/ψ. We have probed this result by searching for decays of $\psi(2S)$ and J/ψ to γ + (π^0, η, η') which proceed via γgg. Of particular interest is the ratio $R_n \equiv B(\psi(nS) \to \eta)/B(\psi(ns) \to \eta')$, which is expected to satisfy $R_1 \simeq R_2$. Previous measurements revealed $R_1 = 20.2 \pm 2.4\%$ and $R_2 < 66\%$ at 90% CL .

We searched for all the above $\gamma+$ pseudoscalar decays of J/ψ, $\psi(2S)$ and $\psi(3770)$ and found[9] that $R_2 << R_1$ at 90% CL. We've tightened the result for R_1, with $R_1 = 21.1 \pm 0.9\%$, and obtain a much lower limit of $R_2 < 1.8\%$ at 90% CL. Such a small value of R_2/R_1 poses a significant challenge to our understanding of these decays.

4.3 Radiative Production of η_c from $\psi(2S)$, J/ψ

The M1 radiative transitions $(\psi(2S), J/\psi) \to \gamma\eta_c$ represent fundamental processes whose rates serve as important benchmarks for theory, but both are very poorly measured. In addition, the partial with measurements of η_c are dependent upon these poor measurements. CLEO-c has made new and much improved measurements[10] of each of these branching fractions.

In this analysis, we measure the yield from the inclusive photon spectrum from $\psi(2S) \to \gamma\eta_c$ and the yields from the exclusive photon spectra (using identical exclusive final states of η_c) from $\psi(2S) \to \gamma\eta_c$ and from $\psi(2S) \to \pi^+\pi^- J/\psi; J/\psi \to \gamma\eta_c$. We obtain $B(\psi(2S) \to \gamma\eta_c)$ from the inclusive photon spectrum, and $B(J/\psi)/B(\psi(2S))$ from the exclusive photon spectra. Multiplying these two numbers yields the branching fraction $B(J/\psi \to \gamma\eta_c)$. We thus find:

$$B(\psi(2S) \to \gamma\eta_c) = (4.32 \pm 0.16 \pm 0.60) \times 10^{-3} \text{ and} \quad (5)$$

$$B(J/\psi \to \gamma\eta_c) = (1.98 \pm 0.09 \pm 0.30)\%. \quad (6)$$

These are each significantly larger than, but much more precise than the previous PDG[4] average, and will result in a renormalization of nearly all exclusive η_c branching fractions. Interestingly the η_c masses reported by experiments which observe η_c in M1 transitions average 5 MeV below those reported by experiments which produce η_c through $\gamma\gamma$ fusion or $\bar{p}p$ annihilation. In our study, we observed that depending on the lineshape assumed, we can obtain a mass consistent with *either* M1 transition or direct-production results. We thus note that a very careful study of the M1 lineshape is clearly in order if the η_c mass is to be extracted from M1 transitions.

5 Summary

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